

RESEARCH MEMORANDUM

CRITICALITY SURVEY OF HYDROXIDES AS COOLANT MODERATORS
FOR AIRCRAFT NUCLEAR REACTORS

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CRITICALITY SURVEY OF HYDROXIDES AS COOLANT MODERATORS FOR

AIRCRAFT NUCLEAR REACTORS

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SUMMARY

Various hydroxides have been screened for use in nuclear reactors as possible coolant moderators for operation at temperatures of about 1500° F. Hydroxides which appear stable at a pressure of about 1 atmosphere are those of sodium, potassium, rubidium, lithium, barium, and strontium (NaOH, KOH, RbOH, LiOH, Ba(OH)₂, and Sr(OH)₂, respectively).

Reflected reactors in which these hydroxides were used have been compared on the basis of enriched uranium investments in order to indicate order of merit. Criticality requirements have been calculated by two-group methods with no allowance for fuel burnup, reactor poisoning, or control requirements.

Minimum core investments of 7 to 13 pounds of enriched uranium are indicated for reflected square cylindrical cores of diameters 1.2 to 1.7 feet moderated, respectively, by Sr(OH)₂, Ba(OH)₂, NaOH, and RbOH; investments for each of these homogeneous reactors for core diameters of 2.0 to 2.5 feet are in the range from 14 to 22 pounds. Minimum investments for reflected reactors with NaOH-KOH eutectic or LiOH with 98 percent of Li⁶ removed are about 30 pounds; investments for reflected reactors with KOH or LiOH with 90 percent of Li⁶ removed are in excess of 115 pounds. Total uranium investments for these homogeneous reactors are, of course, dependent on external circulating volumes and excess reactivity requirements.

For reactors moderated by NaOH, RbOH, Ba(OH)₂, and Sr(OH)₂ and containing the equivalent of 8 percent by volume of iron to represent

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solid fuel elements, cores of diameter 2.0 to 2.5 feet reflected by 0.5 foot of moderator are estimated to require investments of 25 to 35 pounds.

Results are also presented of experimental determinations of the density of liquid NaOH and RbOH for temperatures up to 1700° F. These data, essential to a criticality analysis of reasonable accuracy, are previously unreported.

For hydrogenous reactors containing materials for which there are gaps in cross-section data or for which data are completely lacking in the fast energy region, it is necessary to devise methods for approximating two-group constants. Semiempirical methods for quickly estimating two-group constants are presented.

INTRODUCTION

Liquid hydroxides have long offered many advantages for use as coolant moderators in reactors with solid fuel elements and as coolant-moderator-fuel carriers in homogeneous reactors.

Hydroxides are particularly adaptable for aircraft nuclear propulsion systems because of small reactor sizes resulting from the superior neutron slowing-down properties of hydroxides and the simplified core construction that is possible with avoidance of a separate moderator.

Furthermore, low vapor pressures of hydroxides avoid relatively low-operating-temperature limitations due to boiling, and the small variation of density throughout the temperature range anticipated in aircraft cycle operations is sufficient to insure a negative temperature coefficient of reactivity (see ref. 1).

However, the severe corrosive action of hydroxides on the high-temperature materials available for fuel elements and the solubility limits of uranium salts make the practical application of hydroxides very difficult.

It is the purpose of this report to obtain an indication of the suitability of various hydroxides as coolant moderators with respect to criticality requirements of reactor size and enriched uranium investment. Such a comparison would serve as a guide in determining which hydroxides merited further study with regard to corrosion inhibition. The criterion of uranium investment is employed as a basis from which to judge relative suitability of the various hydroxides without consideration of fuel burnup, reactor poisoning, or control requirements.

A survey of potential hydroxides was made to screen those which appeared suitable for use in a reactor at temperatures of about 1500° F. The hydroxides of lithium, sodium, potassium, rubidium, magnesium, calcium, strontium, barium, aluminum, and zirconium were considered; data for these hydroxides are shown in table I. Nuclear data for solid hydroxides at room temperature were taken from reference 2 and melting and boiling points, wherever available, were taken from reference 3.

2902 Listed values of macroscopic neutron absorption cross section for each hydroxide relative to NaOH indicate that removal of a large fraction of the 7.4 percent abundant Li^6 isotope can bring LiOH into the neutron absorptive range of the other hydroxides.

The question of hydroxide stability at temperatures of interest to the power reactor is an all-important consideration. Therefore, also listed in table I are the vapor and dissociation pressures, or both, to be expected at a temperature of 1500° F. These data were taken from references 3 and 4; the values for $\text{Mg}(\text{OH})_2$, $\text{Al}(\text{OH})_3$, and $\text{Zr}(\text{OH})_4$ were estimated from dissociation data at 1 atmosphere.

In order for criticality calculations to be of reasonable accuracy, it is essential to have data on the density of hydroxides at contemplated operating temperatures of 1500° F. Inasmuch as the only density data available are for liquid NaOH and KOH, and these have been measured at relatively low temperatures (ref. 5), the density of NaOH has been experimentally determined herein for temperatures up to 1700° F. In addition, the density of liquid RbOH has been measured experimentally for temperatures up to 1550° F; the variation of density of RbOH with temperature is taken to be representative of the heavier hydroxides.

Although RbOH is relatively rare, it appears from experience with the density measurements (described in appendix B) that it is very similar to NaOH in stability characteristics. No evidence of boiling was observed on heating RbOH to 1800° F.

SPECIFIC REACTORS

On the basis of the preliminary survey and from consideration of relative neutron absorptivity and stability at high temperature, the hydroxides chosen as possible coolant moderators for the specific reactors investigated are LiOH (enriched in Li^7), NaOH, KOH, NaOH-KOH eutectic, RbOH, $\text{Sr}(\text{OH})_2$, and $\text{Ba}(\text{OH})_2$. The hydroxides $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$, $\text{Al}(\text{OH})_3$, and $\text{Zr}(\text{OH})_4$ have not been further considered because of the pressurization problem they introduce.

No specification of fuel-element materials compatible, on the basis of corrosion, with the hydroxides can be made at present; however, for purposes of comparing the various hydroxides on the basis of criticality requirements, reactor sizes and uranium investments initially have been computed for homogeneous reflected reactors in which uranium is dissolved or suspended in the hydroxides. Two reactors which appeared promising were then recomputed incorporating 8 percent by volume of iron selected to be representative of a fuel-element material. This quantity of material is sufficiently high to provide for a fuel-element design having adequate heat-transfer surface for a reactor of about 300,000 kilowatts.

Data on specific reactors considered are presented in table II; reactor composition and nuclear properties of the reactor materials at an average temperature of 1450° F are listed.

Densities of liquid hydroxides NaOH and KOH were taken from reference 5 and for RbOH from measurements described in appendix B. The density of LiOH was estimated by assuming it to undergo the same percentage change in volume as NaOH in expanding on melting and to have the same temperature coefficient on rising to 1450° F; the densities of the heavier $\text{Sr}(\text{OH})_2$ and $\text{Ba}(\text{OH})_2$ were assumed to expand on melting and heating in the same manner as RbOH (appendix B). Data for eutectic mixtures of NaOH and KOH were taken from reference 6. Neutron cross-section data were taken from references 2, 7, and 8.

Eight homogeneous reactors containing only hydroxide and varying quantities of uranium were investigated to compare the criticality requirements of these coolant moderators. The eutectic of NaOH and KOH with a relatively low melting point of 364° F has operational advantages in starting up reactor systems. Although the eutectic has a composition of 0.528 NaOH - 0.472 KOH by volume, it is 0.613 NaOH - 0.387 KOH on an atomic concentration basis and thus is not so unfavorable absorptionwise as it may at first appear.

Two LiOH reactors are considered in which 90 and 98 percent, respectively, of the highly absorptive Li^6 isotope have been removed. With as much as 98 percent Li^6 removed, the thermal macroscopic absorption cross section of LiOH is about three times greater than that for NaOH.

Relative criticality requirements of homogeneous reactors with the various hydroxides are given by comparing the first eight reactors in table II; total uranium investment required is dependent on the circulating volume of moderator outside the reactor and excess reactivity requirements.

For reactors in which uranium is contained in fuel elements, the effect of neutron absorptivity of the fuel-element material on criticality requirements has been evaluated for two cases: NaOH and NaOH-KOH eutectic, each with 8 percent iron by volume.

A summary of the two-group theory constants for the specific reactors considered is presented in table III. For each reactor, a sufficiently wide range of H to U²³⁵ atom ratio R was covered in order to ensure determination of a reactor size for minimum total uranium investment. Fully enriched uranium is assumed to be uniformly distributed throughout the cores. The two-group core and reflector constants for NaOH, KOH, and NaOH-KOH eutectic were computed by the procedure described in the next section. The two-group constants for RbOH, LiOH, Ba(OH)₂, and Sr(OH)₂ were calculated by the methods described in appendix C for approximate estimation of these constants.

Included in table III is the square root of the core material buckling constant, α_0 , which is simply related to unreflected core sizes of various geometry (see ref. 9).

CRITICALITY CALCULATIONS

The reactor core is taken as a right circular cylinder of length-diameter ratio of unity with fissionable material dissolved or suspended in the hydroxide or contained in suitable fuel elements over which the liquid hydroxide coolant flows. Reactor cores with fuel elements are reflected by circulating hydroxide around the core; homogeneous reactor cores are assumed to be reflected by the equivalent of uranium-free liquid hydroxide.

Two-group neutron diffusion theory was employed in the criticality calculations. Spherical geometry was used in the reactor calculations and a transformation made to cylindrical geometry assuming the reflector savings to remain the same. Reflector savings (defined as the difference between the unreflected and reflected reactor core radii) were found to be relatively independent of core composition, insofar as practical fuel and fuel-element material concentrations are concerned (see ref. 1). The two-group equations were therefore solved for each reflected core for a single uranium concentration corresponding closely to that for minimum total uranium investment; the reflector savings thereby computed for a particular core-reflector combination may be directly applied to each core for the entire range of uranium concentration investigated. Criticality requirements were therefore established for each hydroxide-moderated and -reflected reactor without actually solving the two-group equations for all reflected reactors considered.

Of course, the two-group equations would have to be solved in detail if flux and power distributions were required; however, these are not the main concern here. For any of the reactors considered it would be possible to calculate almost any flux or power distribution desired by nonuniform distribution of uranium (see ref. 10).

Derivation and method of solution of the two-group equations used are briefly reviewed in reference 1 as well as the detailed method for evaluation of the two-group nuclear constants required.

Evaluation of Nuclear Constants

Validity of the two-group procedure depends entirely on the correctness of the nuclear constants used to represent the various competing nuclear processes. To reduce uncertainties in the application of two-group theory, the procedure used in evaluating the two-group constants was patterned, as closely as possible, after that successfully used in reference 11 for small water-moderated reactors.

Procedures for evaluating the two-group constants, which should lead to criticality results sufficiently accurate for engineering evaluation, are briefly outlined as follows (a list of symbols appears in appendix A):

$\lambda_{TR,f}$, K_f , p_{th} . - The fast constants $\lambda_{TR,f}$, K_f , and p_{th} were obtained by weighting local values according to the energy distribution of neutron flux in an infinite medium of the same composition as indicated by age theory. The fission spectrum was included in determining the energy distribution.

L_f^2 . - Mean-square slowing-down lengths were calculated for hydrogenous mixtures by the method of reference 12 in which solutions of the transport equation for the second moment of the spatial distribution of neutrons slowing down from a point source in an infinite medium are given. It was found in reference 12 that a relatively simple approximate formula for L_f^2 (eq. (A3), ref. 12) based on mixtures of heavy elements provides results in excellent agreement with those obtained by the laborious calculations required by the use of the rigorous formula for hydrogenous mixtures. This approximate solution was presently applied to hydroxides, wherever fast cross-section data were available, to obtain L_f^2 as a function of neutron energy. These values of L_f^2 were then weighted over the fission neutron spectrum to obtain an average value of L_f^2 for the fast group. Values so obtained were corrected to the experimental value of L_f^2 for water as described in appendix C of reference 1.

$\lambda_{TR,th}$. - The average thermal transport mean free path $\lambda_{TR,th}$ is given by the sum of the contributions of each constituent atom, the hydrogen atom being the largest contributor. The effects of chemical binding of the hydrogen atom to the molecule, however, significantly alter its thermal scattering properties. The method of reference 13, which checks experimentally determined thermal diffusion properties of water for a range of temperature, was therefore used on the assumption that the chemical binding energy of hydrogen in hydroxides is the same as that in water.

K_{th} , L^2_{th} . - The thermal multiplication constant is calculated from local values of Σ_A and Σ_F assumed to vary with neutron energy according to $1/v$ in the thermal energy region; $\Sigma_{A,th}$ and $\Sigma_{F,th}$ are then obtained by weighting Σ_A and Σ_F according to the flux of neutrons in a Maxwellian distribution corresponding to the moderator temperature. The mean-square thermal diffusion length L^2_{th} is given by

$$L^2_{th} = \frac{\lambda_{TR,th}}{3\Sigma_{A,th}}$$

The thermal multiplication constant K_{th} is given by

$$K_{th} = \frac{\nu\Sigma_{F,th}}{\Sigma_{A,th}}$$

Approximate Method for Evaluating Constants

In the use of the two-group method for enriched uranium reactors moderated by hydrogenous materials and containing elements for which there are large gaps in or complete lack of cross-section data in the fast energy region, it is necessary to devise and evaluate quantitative methods for estimating required parameters.

Based on semiempirical observations regarding the integrated two-group constants for hydroxide-moderated reactors, it is possible to estimate reasonable values of the two-group constants without having to resort to the time-consuming detailed integration procedures referred to in the previous section and described in detail in appendix C of reference 1. A detailed description is presented in appendix C of the present report of the formulation of the procedures for directly estimating the two-group constants and of the agreement obtained with the detailed integration procedures. It is shown that although seven core parameters are required for two-group calculations, there are three independent variables for any given uranium

concentration, namely $\lambda_{TR,th}$, $\lambda_{TR,f}$, and $\Sigma_{A,th}$ that largely determine the other parameters for hydrogenous reactors containing $1/v$ absorbers.

Because of uncertainties in basic cross-section data and in hydroxide densities, and approximations made in evaluating the two-group constants, and because the two-group method of reactor analysis is itself an approximation, the effects of arbitrary variations of ± 10 percent in $\lambda_{TR,th}$, $\lambda_{TR,f}$, and $\Sigma_{A,th}$ and resulting changes in the other dependent two-group constants on criticality predictions have been determined. These calculations and results, discussed in appendix D, are not intended to evaluate probable errors but merely to illustrate the relative sensitivity of the criticality results to a given percentage change in core parameters.

RESULTS OF CRITICALITY CALCULATIONS

Core Uranium Investments

Comparative enriched uranium investment as a function of reflected reactor core diameter for each hydroxide homogeneous reactor is presented in figure 1. Reactor cores are cylinders of length-diameter ratio unity and average moderator temperature is 1450°F ; cores are reflected by 0.5-foot thickness of hydroxide of the same composition as the moderator.

All the curves exhibit characteristic minimum core investments obtained with core diameters below 2 feet for all cases except KOH, for which a core diameter of 3.0 feet is indicated. Inasmuch as the heat-transfer analysis of reactors with solid fuel elements made in reference 1 indicated that NaOH reactor cores about 2.0 to 2.5 feet in diameter were required for anticipated total powers for aircraft propulsion, it is more likely that the lower core investments indicated for diameters below 2 feet may be applicable for homogeneous hydroxide-fuel reactors rather than for solid fuel-element reactors. It is indicated that such homogeneous systems may be made critical with diameters of about 1.2 feet for $\text{Sr}(\text{OH})_2$, 1.4 feet for $\text{Ba}(\text{OH})_2$, 1.6 feet for NaOH, and 1.7 feet for RbOH. Minimum investments for these reflected cores range from 7 to 13 pounds; total uranium investments are, of course, dependent on external circulating volumes and excess reactivity requirements. Criticality investments for these reactors are very closely the same for core diameters in the range from 2.0 to 2.5 feet varying from 14 to 22 pounds in the core.

In figure 1(b), it is observed that KOH requires large investments, in excess of 115 pounds. However, the eutectic composition of NaOH and KOH, which is 0.613 NaOH - 0.387 KOH on an atomic concentration basis, requires a minimum investment of 30 pounds for core diameter of 2.0 feet.

Relative investments for LiOH, with 90 and 98 percent, respectively, of the highly absorptive Li^6 isotope removed, are also presented in figure 1(b). With removal of 98 percent of Li^6 , a minimum investment of 29 pounds is required for core diameter of 1.7 feet.

The effect of fuel-element material in a reactor, evaluated for the NaOH and NaOH-KOH eutectic reactors, is presented in figure 2. A concentration of 8 percent by volume of iron, taken to be representative of the fuel-element material, requires an increase in uranium investment of approximately 50 percent over investments of similar reactors without iron.

The results for NaOH reactor with 8 percent by volume of iron may be used to estimate the investments required for RbOH , $\text{Sr}(\text{OH})_2$, or $\text{Ba}(\text{OH})_2$ reactors inasmuch as homogeneous reactor investments for core diameters of 2.0 to 2.5 feet are very nearly the same (see fig. 1(a)). Reactors having a neutron absorptivity about equivalent to 8 percent iron should therefore require approximately 25 to 35 pounds of enriched uranium in the range of practical core diameters of 2.0 to 2.5 feet.

Reflector Savings

Variation of two-group reflector savings δ for the various reflectors considered is presented in figure 3. Reflector savings have been computed by the two-group method for cores in which the moderator also serves as reflector.

Reflector thickness of 0.5 foot appears to be a good compromise between decreasing core size and increasing core plus reflector size and effectively represents the saturated savings for most of the reflectors considered. For this reason, values of reflector savings corresponding to 0.5-foot-thick reflectors were applied to the unreflected cores.

Reflector savings are very closely equal to reflector thickness t for thin reflectors. From simplified one-group thermal considerations for a slab reactor (see ref. 9), δ for thin reflectors is given approximately by

$$\delta \approx \frac{\lambda_{TR,c}}{\lambda_{TR,r}} t$$

When moderator and reflector are the same material, $\lambda_{TR,c} = \lambda_{TR,r}$; and the result that $\delta = t$ is to be expected. However, from preliminary two-group calculations with reflectors of different composition from the core moderator, it has been found that transport mean free paths of the fast group should be used in the foregoing relation to estimate reflector savings for small values of t .

For relatively thick reflectors, reflector savings vary appreciably and saturate out at different reflector thicknesses. The two-group savings for thick reflectors are dependent on the diffusion and absorption parameters of both fast and thermal groups. From simplified one-group thermal considerations for a slab reactor (see ref. 9), δ for very thick reflectors is given approximately by

$$\delta \approx \frac{\lambda_{TR,c}}{\lambda_{TR,r}} L_{th,r}$$

where $L_{th,r}$ is the square root of the mean square diffusion distance for thermal neutrons in the reflector. However, for the special case of core moderator and reflector composed of the same material ($\lambda_{TR,c} = \lambda_{TR,r}$), it appears that the saturated reflector savings for the two-group diffusion picture are given approximately by the parallel expression

$$\delta \approx \sqrt{L_{f,r}^2 + L_{th,r}^2} = M_r$$

where M_r is the migration length for neutrons in the reflector. The excellent agreement between saturated reflector savings δ as calculated by the two-group method and the migration length M_r for the hydroxide-moderated and -reflected reactors considered is given in the following table:

Reflector-moderator	$L_{f,r}^2$ cm ²	$L_{th,r}^2$ cm ²	M_r cm	δ , cm
NaOH	86.4	67.2	12.39	12.38
KOH	225.0	51.4	16.62	16.61
NaOH-KOH eutectic	127.0	54.9	13.49	13.49
RbOH	100.0	101.0	14.18	13.64
LiOH (0.90 Li ⁶ removed)	91.0	6.7	9.88	9.83
LiOH (0.98 Li ⁶ removed)	91.0	28.0	10.91	10.93
Ba(OH) ₂	70.0	47.9	10.86	10.92
Sr(OH) ₂	50.0	32.9	9.10	9.19

SUMMARY OF RESULTS

Various hydroxides have been screened for use in nuclear reactors as possible coolant moderators for operation at temperatures of about 1500° F. Hydroxides which appear stable at a pressure of about 1 atmosphere are NaOH, KOH, RbOH, LiOH, Ba(OH)₂, and Sr(OH)₂.

Reflected reactors using the hydroxides have been compared on the basis of enriched uranium investments in order to indicate order of merit. Criticality requirements have been calculated by two-group methods with no allowance for fuel burnup, reactor poisoning, or control requirements.

Minimum core investments are obtained with reflected square cylindrical cores of diameters below 2 feet for all cases except KOH. Minimum enriched uranium investments and corresponding core diameter for homogeneous reactors reflected by 0.5 foot of moderator are listed in the following table. Total uranium investments are, of course, dependent on external circulating volumes and excess reactivity requirements.

Coolant-moderator fuel-carrier	Minimum uranium investment, lb	Reactor core diameter, ft
Sr(OH) ₂	7	1.2
Ba(OH) ₂	10	1.4
NaOH	12	1.6
RbOH	13	1.7
LiOH (0.98 Li ⁶ removed)	29	1.7
NaOH-KOH eutectic	30	2.0
KOH	115	3.0
LiOH (0.90 Li ⁶ removed)	130	1.9

Incorporation of 8 percent by volume of iron to represent solid fuel elements is calculated to increase uranium investments by about 50 percent for the NaOH and NaOH-KOH eutectic reactors for core diameters greater than those corresponding to minimum uranium investment. Approximately the same increase due to the presence of fuel-element material equivalent to 8 percent by volume of iron is estimated to apply to all the hydroxides considered.

For reactors moderated by NaOH, RbOH, Ba(OH)₂, and Sr(OH)₂ and containing the equivalent of 8 percent by volume of iron, cores of diameter 2.0 to 2.5 feet reflected by 0.5 foot of moderator are

estimated to require enriched uranium investments from 25 to 35 pounds.
(These core diameters are considered practical with respect to heat transfer for reactor heat releases of the order of 300,000 kw.)

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 1, 1953

APPENDIX A

SYMBOLS

E	neutron energy
K	neutron multiplication constant
L^2_f	mean square slowing-down distance for fast neutrons
L^2_{th}	mean square diffusion distance for thermal neutrons
M^2	migration area, $(L^2_f + L^2_{th})$
N	reactor atom density
p_{th}	resonance escape probability
R	atom ratio of hydrogen to uranium 235
T	temperature, °F
t	reflector thickness
v	neutron velocity
α_0	square root of core buckling constant
δ	reflector savings
λ_{TR}	macroscopic transport mean free path
ν	neutrons produced per fission
ξ	average logarithmic energy loss per collision
ρ	moderator density
Σ	macroscopic cross section
σ	microscopic cross section

Subscripts:

A	absorption
c	core

F	fission
f	fast neutron group
r	reflector
S	scattering
th	thermal neutron group
TR	transport

APPENDIX B

EXPERIMENTAL DENSITY DETERMINATION

The densities of liquid NaOH and RbOH were measured for temperatures up to 1700° F. The loss of weight due to buoyancy of cylindrical nickel plummets of approximately 5-cubic-centimeter displacement, suspended in molten hydroxide by nickel wire, was measured by a precision beam balance. The hydroxides were contained in a cylindrical nickel crucible and were gradually heated in a tube furnace controlled by a Variac.

Temperatures were measured by two chromel-alumel thermocouples spot-welded to the outer wall of the crucible and connected to a direct-reading potentiometer. Temperatures were also checked by directly immersing a thermocouple into the hydroxide; all temperatures generally agreed within 20° F.

The volume of the nickel plummet for each temperature was corrected for volumetric expansion; this correction is about 5 percent at 1800° F.

Chemical analysis of the hydroxides used indicated the following initial composition in percent by weight.

NaOH	97.6	RbOH	90.4
Na ₂ CO ₃	0.3	Rb ₂ CO ₃	2.1
H ₂ O	2.1	H ₂ O	7.5

NaOH. - The density measurements for NaOH in the temperature range 1250° to 1700° F are presented in figure 4. The density data of reference 5 measured in the low temperature region are also indicated. The present data confirm the trend with temperature. The equation of the straight line shown is

$$\rho = 1.945 - 0.000263 T$$

where ρ is in grams per cubic centimeter and T in °F.

White vapors were observed leaving the crucible during the tests. When the nickel crucible was washed out, a considerable number of small black crystals were formed during the cooling period of about ten hours; they would not have interfered with the density measurements which were completed during a heating time of about two hours. Loss of weight due to corrosion of the nickel plummet was negligible during the tests.

RbOH. - The density measurements for RbOH are presented in figure 5. The data for two sets of measurements on successive days are given. For the first set, the RbOH was found to melt gradually in the temperature range 400° to 500° F. Density measurements from 500° to 900° F exhibited the reversal shown, which is attributed to the change in properties encountered in driving off water from the partly hydrated RbOH. From 900° to 1550° F, the density variation with temperature was linear.

During the second set of measurements, the hydroxide was observed to melt at a temperature above 700° F. Density measurements in the range 750° to 1250° F were in agreement with the linear portion of the first set of measurements, indicating no further changes in composition.

The equation of the straight line is shown

$$\rho = 3.126 - 0.000434 T$$

White vapors were observed leaving the crucible at temperatures above 900° F. The nickel wire supporting the plummet failed at a melt temperature of about 1650° F. The melt was further heated to about 1800° F at which temperature the thermocouples failed. No unusual vapors or evidences of boiling were observed at these temperatures and the melt was light yellow and similar in appearance to NaOH at these temperatures. Stability characteristics of RbOH therefore appear similar to those of NaOH. Small black crystals were found when the crucible was washed out.

The melting point of the dehydrated RbOH salt used is more accurately determined by the cooling curve shown in figure 6. The transition is observed to occur at 722° F. This value disagrees with a melting point of 572° F for RbOH reported in reference 6. The cooling curves presented in reference 6 indicate the highest temperature of the melt used to be about 700° F. If the RbOH sample used were partly hydrated to begin with, the experience with the present density measurements would indicate that a lower melting point is to be expected. The partly hydrated RbOH melted at slightly above 500° F, but was not completely dehydrated until heated above 900° F in the present tests.

The specific gravity of solid RbOH used was measured to be 3.000 in comparison to the value of 3.203 reported in reference 6.

APPENDIX C

APPROXIMATE METHOD OF EVALUATING TWO-GROUP CONSTANTS

In the use of the two-group method for calculating enriched uranium reactors moderated by hydrogenous materials, it is necessary to devise methods for approximating two-group constants for reactors containing materials for which there are gaps in cross-section data or for which data are completely lacking in the fast energy region.

The constants required for solution of the two-group equations are ordinarily separately evaluated for each core and reflector composition. The thermal parameters required are

$$\lambda_{TR,th}, K_{th}, L_{th}^2$$

The fast parameters required are

$$p_{th}, K_f, L_f^2, \lambda_{TR,f}$$

Evaluation of these average group constants by the procedures briefly mentioned earlier and described in detail in reference 1 have led to semiempirical methods of estimating the two-group constants for hydrogenous reactors which avoid the rather lengthy numerical calculations ordinarily required. It will be shown that although seven core parameters are required for two-group calculations, there are three independent variables for any given uranium concentration, namely $\lambda_{TR,th}$, $\lambda_{TR,f}$, and $\Sigma_{A,th}$, that largely determine the other parameters for hydrogenous reactors containing $1/v$ absorbers. Furthermore, the accuracy with which all of the two-group constants may be directly evaluated is within a few percent of the values obtained by the numerical methods. All values, of course, are subject to the broad assumptions and limitations inherent in the two-group diffusion procedure of reactor analysis.

$\lambda_{TR,th}$ - The method of reference 13 for estimating the effect of chemical binding of hydrogen to the molecule on thermal neutron diffusion in a hydrogenous medium is used to evaluate $\lambda_{TR,th}$. By this method experimental values of thermal diffusion length for water have been checked for temperatures up to 600° F.

The contribution to $\lambda_{TR,th}$ which is due to the hydrogen λ_{TR}^H is given by

$$\lambda_{TR}^H = \frac{1}{N^H \bar{\sigma}_{TR}^H}$$

This relation permits the determination of an effective value of microscopic transport cross section $\bar{\sigma}_{TR}^H$ for hydrogen. Under the assumption that the chemical binding of hydrogen in any hydroxide moderator is essentially the same as that in water, $\bar{\sigma}_{TR}^H$ may be uniquely determined for any moderator temperature. The variation of $\bar{\sigma}_{TR}^H$ with temperature as determined from the thermal diffusion properties of water and the method of reference 13 is presented in figure 7.

The value of $\lambda_{TR,th}$, for all constituents of the reactor is then given by

$$\lambda_{TR,th} = \frac{1}{N^H \bar{\sigma}_{TR}^H + N_1 \sigma_{TR,1} + N_2 \sigma_{TR,2} + \dots + N_n \sigma_{TR,n}}$$

inasmuch as $\sigma_{TR,n}$ for all other reactor constituents are directly calculable.

K_{th} , L_{th}^2 . - The remaining thermal parameters, K_{th} and L_{th}^2 , are directly calculable from their definitions.

$$K_{th} = v \frac{\Sigma_{F,th}}{\Sigma_{A,th}} = v \frac{\Sigma_{F,(0.025)}}{\Sigma_{A,(0.025)}}$$

with assumption of $1/v$ variation of uranium absorption and fission cross sections in the thermal region.

$$L_{th}^2 = \frac{1}{3} \frac{\lambda_{TR,th}}{\Sigma_{A,th}}$$

where $\Sigma_{A,th}$ is the value of absorption cross section for all reactor constituents averaged over the Maxwellian distribution of neutron flux. For absorption cross sections which follow the $1/v$ law, the value of $\Sigma_{A,th}$ is exactly $\sqrt{\pi}/2$ or 0.886 of the absorption cross section corresponding to the neutron flux at the most probable energy to which it is customary to refer measured cross sections.

p_{th} . - The so-called resonance escape probability p_{th} for highly enriched uranium reactors containing absorbers which effectively follow

the $1/v$ law is not completely a measure of resonance absorption as such, but principally a measure of absorption which occurs because the $1/v$ component extends into the region just above thermal energies.

The probability that a neutron will escape capture in slowing down from birth energy E_0 to thermal energy E_{th} in infinite hydrogenous moderators containing heavy absorbers is given by equation 6.88.1 of reference 9

$$P_{th} = \exp \left[- \int_{E_{th}}^{E_0} \frac{\Sigma_A dE}{(\Sigma_A + \Sigma_S)E} \right]$$

This equation can be evaluated for $1/v$ absorbers to provide P_{th} as an explicit function of certain thermal parameters.

For media containing appreciable amounts of hydrogen, almost all neutron moderation is due to hydrogen. Also, for a considerable range of absorptivity, the quantity $(\Sigma_A + \Sigma_S)$ can be approximated by Σ_S . (For the most absorptive reactor considered, the value of Σ_A was about 10 percent of Σ_S ; this percentage would increase slightly for thermal energies corresponding to temperatures lower than 1450° F.)

Inasmuch as Σ_S^H comprises more than 95 percent of the total scattering for hydroxide reactors, the quantity Σ_S is closely given by

$$\Sigma_S \approx \Sigma_S^H = N^H \bar{\sigma}_S^H$$

where $\bar{\sigma}_S^H$ is an effective constant value for the epithermal region. If all reactor absorbers are assumed to follow the $1/v$ law in this region, the expression for P_{th} therefore becomes

$$\begin{aligned} P_{th} &= \exp \left[- \frac{\Sigma_{A,0.025} (0.025)^{\frac{1}{2}}}{N^H \bar{\sigma}_S^H} \int_{E_{th}}^{E_0} \frac{dE}{E^{3/2}} \right] \\ &= \exp \left[- \frac{2\Sigma_{A,0.025}}{N^H \bar{\sigma}_S^H} \left(\frac{0.025}{E_{th}} \right)^{\frac{1}{2}} \right] = \exp \left(- \frac{2\Sigma_{A,th}}{N^H \bar{\sigma}_S^H} \right) \end{aligned}$$

Only energies in the neighborhood of E_{th} contribute significantly to the integral.

For convenience, the parameter K_{th} is introduced as follows:

$$K_{th} = \frac{v \Sigma_{F,th}^U}{\Sigma_{A,th}} = \frac{v \Sigma_{F,0.025}^U}{\Sigma_{A,0.025}}$$

Therefore

$$p_{th} = \exp \left[- \frac{2v N^U \sigma_{F,0.025}^U}{K_{th} N^H \bar{\sigma}_S^H} \left(\frac{0.025}{E_{th}} \right)^{\frac{1}{2}} \right]$$

For a range of thermal energies of interest, corresponding to average moderator temperatures from 1000° to 2000° F, a value of $\bar{\sigma}_S$ of 25 barns provides very good agreement with values of p_{th} obtained by numerical integration so that the expression for p_{th} becomes

$$p_{th} = \exp \left[- \frac{(2)(2.5)(545)}{K_{th} R(25)} \left(\frac{0.025}{E_{th}} \right)^{\frac{1}{2}} \right] = \exp \left[- \frac{109}{K_{th} R} \left(\frac{0.025}{E_{th}} \right)^{\frac{1}{2}} \right]$$

which for the thermal energy of 0.092 electron volts corresponding to a temperature of 1450° F becomes simply

$$p_{th} = e^{-57/K_{th}R}$$

A comparison of p_{th} computed by the foregoing equations and by detailed numerical integration is shown in figure 8 for various average moderator temperatures for two NaOH-U mixtures and in figure 9 as a function of K_{th} for various reactors at 1450° F.

K_f . - The average fast multiplication constant K_f , given by $\frac{v \Sigma_{F,f}}{\Sigma_{A,f}}$, would be equal to K_{th} if all neutron absorbers strictly followed the $1/v$ law. However, uranium exhibits fission and absorption cross sections which depart from the $1/v$ law in the resonance region. Although deviations from $1/v$ variation do not contribute on the average to p_{th} , they do affect the ratio of productive to nonproductive absorption in U^{235} and so affect K_f .

For reactors of practical interest, numerical values of K_{th} vary from 1.0 to 2.0. The lower value corresponds to large thermal reactors for which uranium is proportionally a small absorber; the higher value corresponds to intermediate reactors for which uranium is proportionally a large absorber. The maximum value K_{th} may have is 2.11 for a mixture of uranium and nonabsorptive material.

Inasmuch as uranium cross sections in the fast energy region exhibit many resonances, values of K_f can be determined only by numerical integration. However, once determined, K_f may be correlated with K_{th} for reactors in which fast production is in the epithermal region. The variation of K_f with K_{th} for all the reactors of reference 1 and present data for KOH and NaOH-KOH eutectic are shown in figure 10. For these reactors K_f has been numerically evaluated by weighting both $\Sigma_{T,f}$ and $\Sigma_{A,f}$ according to the neutron flux in an infinite medium of the same composition as the reactor of interest. All the data fall on a single curve; the higher values for K_f are progressively smaller than K_{th} because of the increasing fraction of nonproductive absorption in uranium in the epithermal region. Figure 10 therefore serves to identify an appropriate value of K_f to be employed with any value of K_{th} for reactors in which the greatest contribution to K_f is in the epithermal region and not in the very fast region.

$\lambda_{TR,f}$. - The fast transport mean free path $\lambda_{TR,f}$ has usually been evaluated by weighting local energy values by the flux in an infinite medium and averaging over the entire fast region.

It has been found possible to estimate directly the average values of $\lambda_{TR,f}$ calculated by the foregoing procedure if average values of σ_g for the reactor constituents in the region of 0.1-0.5 MEV are used. For example, values of $\bar{\sigma}_g$ for the elements presently under consideration, listed in the following table, permit estimation of $\lambda_{TR,f}$ to within a few percent of the values obtained by the detailed integration over the fast region. This simple estimate is well within the accuracy of the two-group method.

Atom	Average fast scattering cross section, $\bar{\sigma}_S$, barns
H	12.0
O	3.5
Na	4.0
K	1.5
Rb	10.5
Li	1.5
Ba	6.0
Sr	8.0
Fe	3.5
Ni	6.0
Zr	7.0
Al	3.5

L^2_f . - The mean square slowing down length L^2_f for hydrogenous infinite media is, in the absence of specific experimental information, best estimated by the method of reference 12. These calculated values are corrected to the available experimental information for water as described in reference 1. The method of reference 12, however, can be applied only when cross-section data in the fission energy region are known.

Of the elements under consideration, H, O, Na, Ba, and Fe are the only ones for which fast cross-section data are known. Only thermal data or very sparse fast data are available for K, Rb, Li⁷, and Sr. It is therefore necessary to assume values for missing fast data and employ the method of reference 12 or make use of existing calculated L^2_f data for various metal-water mixtures such as Zr-H₂O (ref. 14), or Al-H₂O (ref. 15), or Ni-H₂O (unpublished data). According to reference 12, slowing down in a hydrogenous medium depends on the density of hydrogen nuclei and on the scattering of heavy nuclei relative to the scattering of hydrogen nuclei.

Inasmuch as less than 5 percent of the slowing down is due to the metal and oxygen in these metal-water mixtures and the remainder due to hydrogen, the actual composition of the heavy elements in itself is not important. The heavy elements are accounted for by their scattering properties relative to those of hydrogen. On this basis it should be possible to correlate the existing calculated values of L^2_f for mixtures having a value of atomic density of hydrogen nuclei equal to that in a reference mixture (in water of unit density, for example) with a relative scattering ratio

$$\frac{N^{\text{Heavy}} \bar{\sigma}_S^{\text{Heavy}}}{N^{\text{H}} \bar{\sigma}_S^{\text{H}}} = \frac{\Sigma_S^{\text{Heavy}}}{\Sigma_S^{\text{H}}}$$

Average values of σ_S in the region of 0.1-0.5 MEV (as employed in the foregoing section to estimate $\lambda_{\text{TR},f}$) for all elements of present interest are listed in the table in the foregoing section. The relative scattering ratio $\Sigma_S^{\text{Heavy}}/\Sigma_S^{\text{H}}$ and the calculated values of L^2_f adjusted to a reference hydrogen atomic density of 0.0668×10^{24} (water of unit density) for each of the mixtures calculated by the method of reference 12 are listed in table IV.

The variation of adjusted mean square slowing down length $L^2_f \left(\frac{N^{\text{H}}}{N^{\text{H}}_{\text{ref}}} \right)^2$ with $\Sigma_S^{\text{Heavy}}/\Sigma_S^{\text{H}}$ is presented in figure 11. Also included in figure 11 are the data for NaOH, NaOH-KOH eutectic, KOH, Ba(OH)₂, NaOH and eutectic with iron mixtures calculated in the present report, and the NaOH mixtures calculated in reference 1.

A reasonable correlation is obtained. This curve was used to estimate the value of L^2_f for RbOH in the following way. The value of relative scattering ratio for RbOH is

$$\frac{\Sigma_S^{\text{Heavy}}}{\Sigma_S^{\text{H}}} = \frac{N^{\text{H}}(\bar{\sigma}_S^{\text{Rb}} + \bar{\sigma}_S^{\text{O}})}{N^{\text{H}} \bar{\sigma}_S^{\text{H}}} = \frac{0.0147 (10.5 + 3.5)}{0.0147 (12)} = 1.17$$

so that

$$L^2_f \left(\frac{N^{\text{H}}}{N^{\text{H}}_{\text{ref}}} \right)^2 = 5.0$$

$$L^2_f = 5.0 \times \left(\frac{0.0668}{0.0147} \right)^2 = 102.5$$

APPENDIX D

EFFECTS OF ARBITRARY VARIATION IN TWO-GROUP CONSTANTS
ON CRITICALITY PREDICTIONS

It would be instructive to see the effects of an arbitrary variation in the two-group constants on criticality predictions inasmuch as the two-group constants and procedure are subject to errors due to lack of basic nuclear data, approximations in determining average group constants, uncertain moderator densities at high temperature, and neglect of resonance absorption and inelastic scattering, and because the two-group method of reactor analysis is itself an approximation. These calculations are not intended to evaluate probable errors but merely to illustrate the relative sensitivity of the criticality results to a given percentage change in core parameters.

From the procedures for rapidly estimating the two-group constants (appendix C), it may be observed that although there are seven core parameters, there are three independent variables for any given uranium concentration which may introduce uncertainty. These are $\lambda_{TR,th}$, $\lambda_{TR,f}$, and $\Sigma_{A,th}$; the other parameters are effectively functions of these three for the hydrogenous reactors considered.

Arbitrary and separate increments of ± 10 percent in each of the parameters and in moderator density have been taken for the homogeneous NaOH reactor. The results are presented in figure 12 in which enriched uranium investment is presented as a function of reflected reactor core diameter. The curves are designated by plus or minus signs to indicate a ± 10 percent increment in the particular parameter. Reflector savings for 0.5-foot thickness of NaOH are maintained for all cases.

The 10-percent change in $\lambda_{TR,th}$ and the corresponding change in L^2_{th} are seen to have a negligible effect on the criticality requirements.

A 10-percent change in $\lambda_{TR,f}$, effecting approximately a 20-percent change in the same direction for L^2_f due to change in Σ_g also, has a significant effect on criticality requirements, causing about a 50-percent change in the minimum investment and altering its position slightly. In the core size region of interest (diameters of 2.0 to 2.5 ft), investments are altered by about 20 percent.

Finally, a 10-percent increase in $\Sigma_{A,th}$ which, for illustration purposes, is attributed to uncertainties in the absorption cross sections but not in the fission cross section of uranium, effects a 10-percent decrease in K_{th} and corresponding decreases in K_f , p_{th} , and L^2_{th} . This results in a change in criticality investment of approximately 30 percent for core diameters of 2.0 to 2.5 feet.

Another pertinent case to consider is the change in criticality resulting from uncertainties in moderator density. Although densities for NaOH, KOH, and RbOH are accurately known from experimental determination, densities of LiOH, $Sr(OH)_2$, and $Ba(OH)_2$ have had to be estimated.

Therefore, a 10-percent decrease in moderator density for homogeneous reactors, which increases $\lambda_{TR,f}$ and $\lambda_{TR,th}$ by 10 percent and increases L^2_f and L^2_{th} by about 20 percent, has been arbitrarily selected. The parameters p_{th} , K_f , and K_{th} do not change at all since they are dependent on microscopic cross sections only. Investments are seen to be affected approximately 20 percent for core diameters of 2.0 to 2.5 feet, for change in density of ± 10 percent.

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TABLE I. - PROPERTIES OF HYDROXIDES

[Nuclear data based on solid hydroxide at room temperature.]

Hydroxide	Specific gravity (solid)	Molecules per cc	Thermal cross section $\sigma_a(0.025 \text{ ev})$, barns	Macroscopic cross section $\Sigma_A(0.025 \text{ ev})$, cm^{-1}	$\frac{\Sigma_A}{\text{NaOH}}$	Melting point, $^{\circ}\text{F}$	Boiling point, $^{\circ}\text{F}$	Vapor or dissociation pressure at $.1500^{\circ}\text{ F}$, mm Hg
Li^7OH	1.430	0.0360×10^{24}	0.35	0.0126	0.50	842	Dissociates	300
LiOH	1.430	.0360	67.22	2.420	95.6	842	Dissociates	300
NaOH	2.130	.0321	.79	.0253	1.00	605	2535	5
KOH	2.044	.0220	2.37	.0522	2.06	680	2410	7
RbOH	3.203	.0188	1.02	.0192	.76	572	>1800	
$\text{Mg}(\text{OH})_2$	2.380	.0246	.70	.0172	.68	662	Dissociates	$\sim 500,000$
$\text{Ca}(\text{OH})_2$	2.343	.0191	1.05	.0201	.79	1076	Dissociates	30,000
$\text{Sr}(\text{OH})_2$	3.625	.0180	1.80	.0324	1.28	707	Dissociates	1,000
$\text{Ba}(\text{OH})_2$	4.500	.0086	1.69	.0145	.57	173	1436	130
$\text{Al}(\text{OH})_3$	2.423	.0187	1.18	.0221	.87	572	Dissociates	$>10^6$
$\text{Zr}(\text{OH})_4$	3.250	.0123	1.50	.0184	.73	1022	Dissociates	$\sim 30,000$

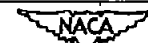


TABLE II. - SPECIFIC REACTOR COMPOSITIONS AND NUCLEAR PROPERTIES OF MATERIALS

(a) Reactor compositions.

Reactor composition by volume (exclusive of U^{235})	Moderator density ^a	
	g/cc	Molecules/cc
1.00 NaOH	1.57	0.02360×10^{24}
1.00 KOH	1.55	.01665
0.528 NaOH + 0.472 KOH (eutectic)	1.56	.02033
1.00 RbOH	2.50	.01470
1.00 LiOH (0.90 Li^6 removed)	1.04	.02630
1.00 LiOH (0.98 Li^6 removed)	1.04	.02630
1.00 $Sr(OH)_2$	3.08	.01524
1.00 $Ba(OH)_2$	3.67	.01289
0.92 NaOH + 0.08 Fe	1.57	.02360
0.92 NaOH-KOH eutectic + 0.08 Fe	1.56	.02033

^aDensities are for liquid hydroxide at average temperature of 1450° F.

(b) Nuclear properties.

Atom	Thermal neutron cross sections, ^a barns	
	Absorption, σ_A	Scattering, σ_S
Na	0.24	3.0
K	1.02	1.5
Rb	.37	12.0
Li (0.90 Li^6 removed)	3.55	1.4
Li (0.98 Li^6 removed)	.72	1.4
Sr	.58	10
Ba	.58	8
O	.0005	3.9
H	.17	(fig. 5)
Fe	1.24	10.9
U	299	12.0
	250 (σ_F)	

^aThermal energy $E_{th} = 0.092$ ev corresponding to average temperature of 1450° F.



TABLE III. - TWO GROUP THEORY REACTOR CONSTANTS

(a) Cores.

Core composition by volume	$R = \frac{N^H}{N^D}$	$\lambda_{TR,f}$ (cm)	$\lambda_{TR,th}$ (cm)	L_f^2 (cm ²)	L_{th}^2 (cm ²)	K_f	K_{th}	P_{th}	α_o ($\frac{1}{cm}$)
1.00 NaOH	50	3.84	1.74	89.2	4.30	1.750	1.961	0.549	0.0962
	500				27.61	1.213	1.247	.917	.0453
1.00 KOH	50	7.12	2.72	228.0	8.58	1.615	1.749	.543	.0540
	100				14.72	1.440	1.501	.700	.0446
	200				22.92	1.160	1.169	.800	.0258
0.528 NaOH + 0.472 KOH (eutectic mixture)	50	5.02	2.09	130.1	5.78	1.708	1.873	.560	.0767
	200				17.55	1.362	1.422	.827	.0524
	400				26.58	1.077	1.096	.885	.0226
1.00 RbOH	100	3.80	2.10	102.5	15.24	1.638	1.778	.726	.0783
	200				26.48	1.466	1.544	.831	.0631
	400				41.94	1.200	1.223	.890	.0389
1.00 LiOH (0.90 Li ⁶ removed)	20	4.51	1.74	92.7	1.33	1.568	1.680	.183	.0795
	50				2.56	1.260	1.293	.414	.0539
	80				3.34	1.047	1.052	.508	.0228
1.00 LiOH (0.98 Li ⁶ removed)	60	4.51	1.74	92.7	4.23	1.638	1.779	.586	.0862
	100				6.41	1.520	1.615	.703	.0767
	300				13.16	1.100	1.108	.843	.0319
1.00 Ba(OH) ₂	50	3.75	1.56	71.6	3.12	1.735	1.936	.555	.1064
	200				10.23	1.495	1.586	.835	.0823
	500				18.78	1.145	1.164	.907	.0424
1.00 Sr(OH) ₂	50	2.78	1.27	51.0	2.15	1.735	1.936	.553	.1261
	200				7.04	1.495	1.586	.835	.0978
	500				12.93	1.150	1.164	.907	.0504
0.92 NaOH + 0.08 Fe	50	3.75	1.74	90.0	4.45	1.682	1.844	.539	.0904
	150				10.80	1.422	1.492	.783	.0684
	300				16.78	1.145	1.160	.849	.0385
0.92 eutectic + 0.08 Fe	50	4.60	2.37	128.5	6.64	1.621	1.755	.543	.0718
	100				11.49	1.442	1.510	.701	.0591
	200				18.01	1.173	1.181	.801	.0352

(b) Reflectors.

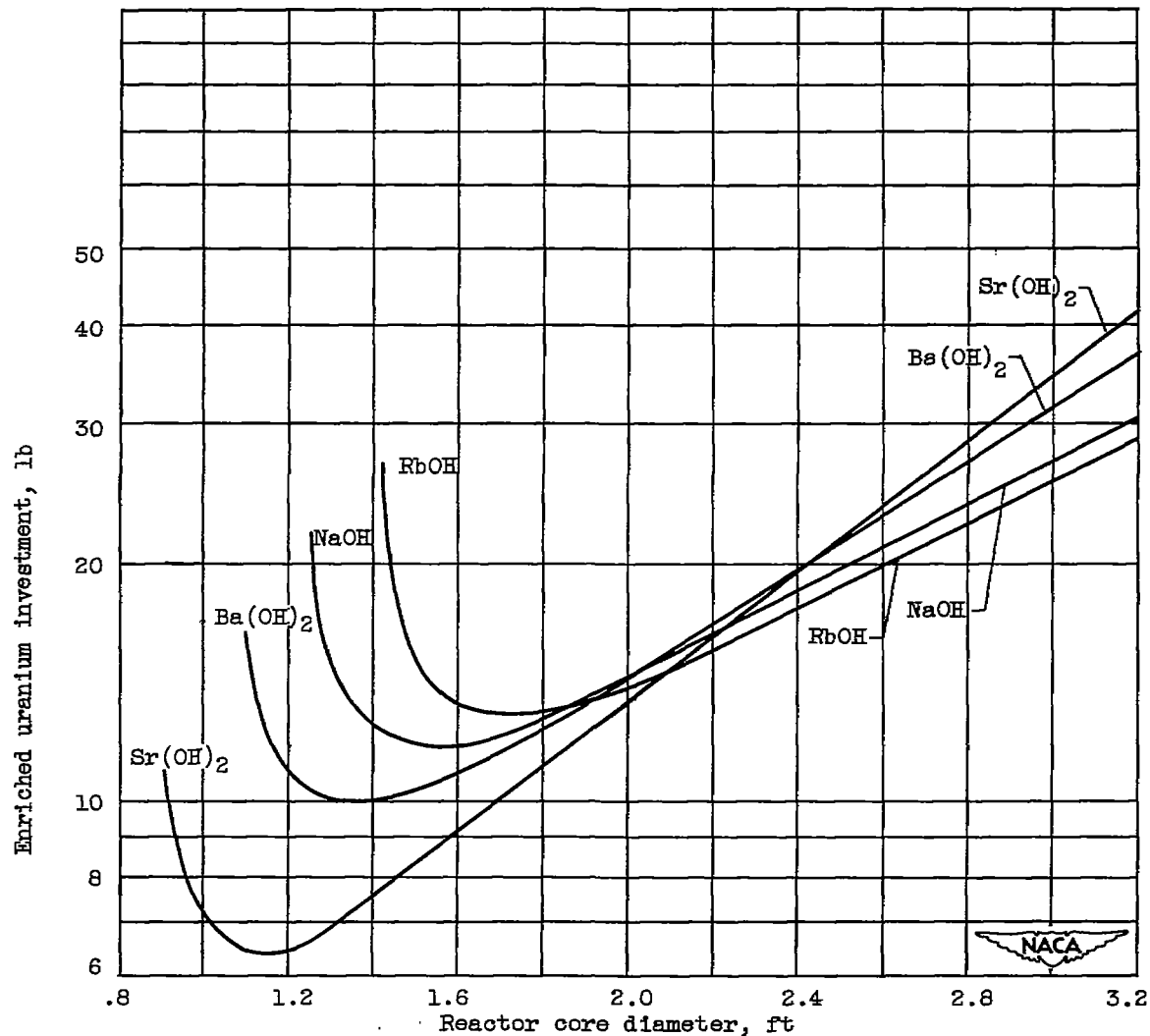
Reflector material	$\lambda_{TR,f}$	$\lambda_{TR,th}$	L_f^2	L_{th}^2	P_{th}
NaOH	3.82	1.73	86.4	67.2	0.970
KOH	7.08	2.71	225.0	51.4	.917
NaOH-KOH eutectic	5.00	2.10	127.0	54.9	.950
RbOH	3.80	2.10	100.0	101.0	.964
LiOH	4.51	1.74	91.0	6.7	.770
(0.90 Li ⁶ removed)					
LiOH	4.51	1.74	91.0	28.0	.940
(0.98 Li ⁶ removed)					
Ba(OH) ₂	3.75	1.56	70.0	47.9	.963
Sr(OH) ₂	2.78	1.27	50.0	32.9	.966

TABLE IV. - CALCULATED VALUES OF L^2_f FOR
VARIOUS METAL-WATER MIXTURES



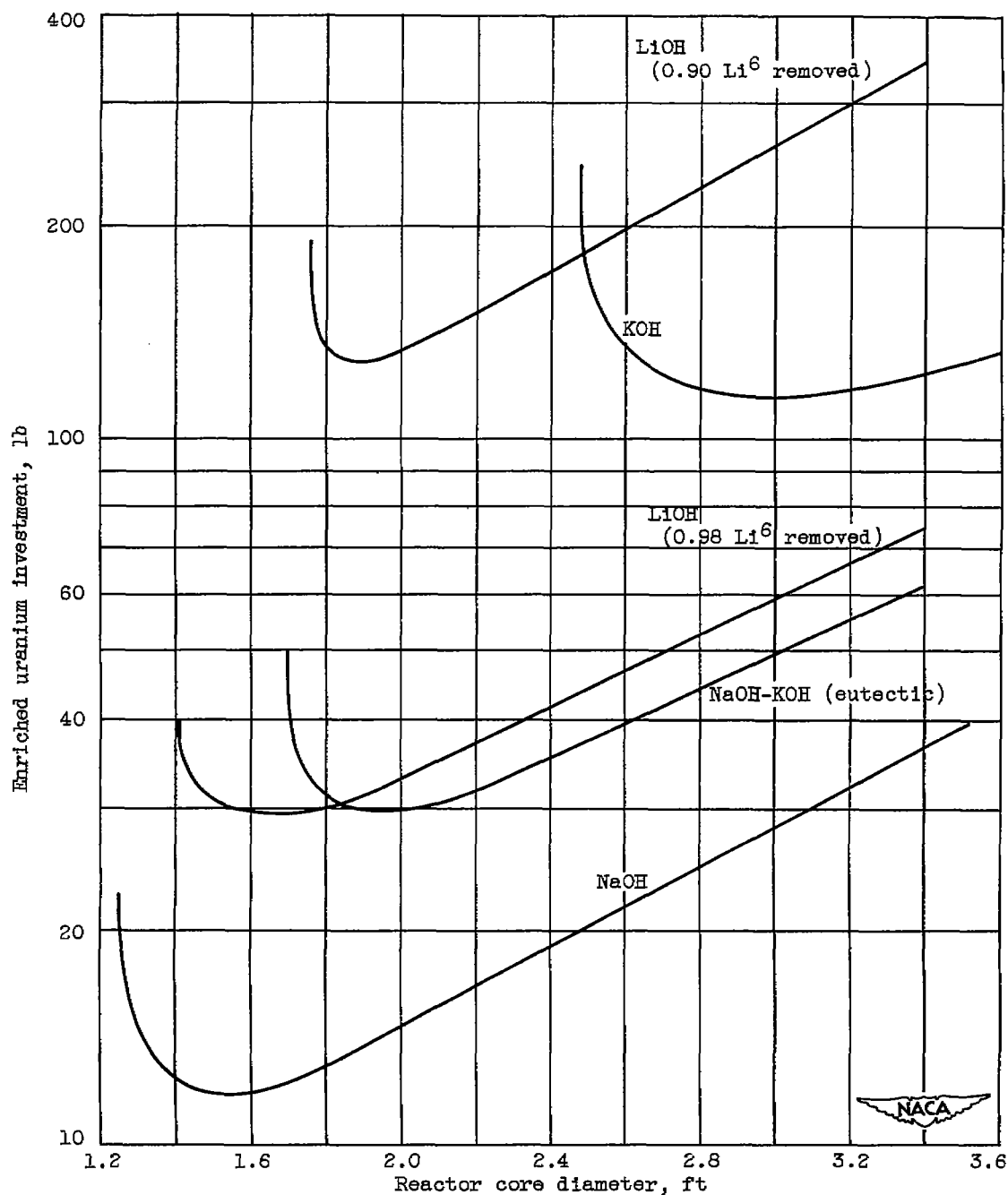
Moderator composition (volume)	$L^2_f^*$ (cm ²)	Reference	$\frac{\Sigma S^{\text{Heavy}}}{\Sigma S^{\text{H}}}$	$L^2_f \left[\frac{N^{\text{H}}}{N^{\text{H}}_{\text{ref.}}} \right]^2$
1.00 H ₂ O	33.0	10	0.146	33.0
0.333 Zr + 0.667 H ₂ O	44.6	15	.340	19.8
0.500 Zr + 0.500 H ₂ O	57.3	15	.521	14.3
0.667 Zr + 0.333 H ₂ O	82.5	15	.898	9.2
0.333 Al + 0.667 H ₂ O	52.2	16	.278	23.2
0.500 Al + 0.500 H ₂ O	74.0	16	.409	18.5
0.667 Al + 0.333 H ₂ O	95.5	16	.673	10.6
0.200 Ni + 0.800 H ₂ O	33.9	Unpub.	.316	21.7
0.500 Ni + 0.500 H ₂ O	41.0	Unpub.	.829	10.2
1.00 NaOH	89.2	Present report	.625	11.2
1.00 KOH	228.0	Present report	.459	14.2
0.528 NaOH + 0.472 KOH	130.1	Present report	.561	12.8
1.00 Ba(OH) ₂	71.6	Present report	.542	15.3
0.92 NaOH + 0.08 Fe	90.0	Present report	.716	9.5
0.92 NaOH-KOH + 0.08 Fe	128.5	Present report	.611	13.5
0.90 NaOH + 0.10 Na	104.9	1	.656	10.6
0.82 NaOH + 0.10 Na + 0.08 Fe	105.6	1	.761	8.9
0.82 NaOH + 0.10 Na + 0.08 Ni	102.0	1	.847	8.6

*Calculated values of L^2_f corrected to agree with experimental value of 33 sq cm for pure H₂O of unit density (see refs.).



(a) Hydroxides of strontium, barium, sodium, and rubidium.

Figure 1. - Enriched uranium investment for hydroxide cooled, moderated, and reflected homogeneous reactors. Reflector thickness, 0.5 foot; length-diameter ratio of cylindrical core, 1.0; average moderator temperature, 1450° F.



(b) Hydroxides of sodium, potassium, sodium-potassium eutectic, and lithium with 0.90 and 0.98 of Li^6 removed.

Figure 1. - Concluded. Enriched uranium investment for hydroxide cooled, moderated, and reflected homogeneous reactors. Reflector thickness, 0.5 foot; length-diameter ratio of cylindrical core, 1.0; average moderator temperature, 1450° F.

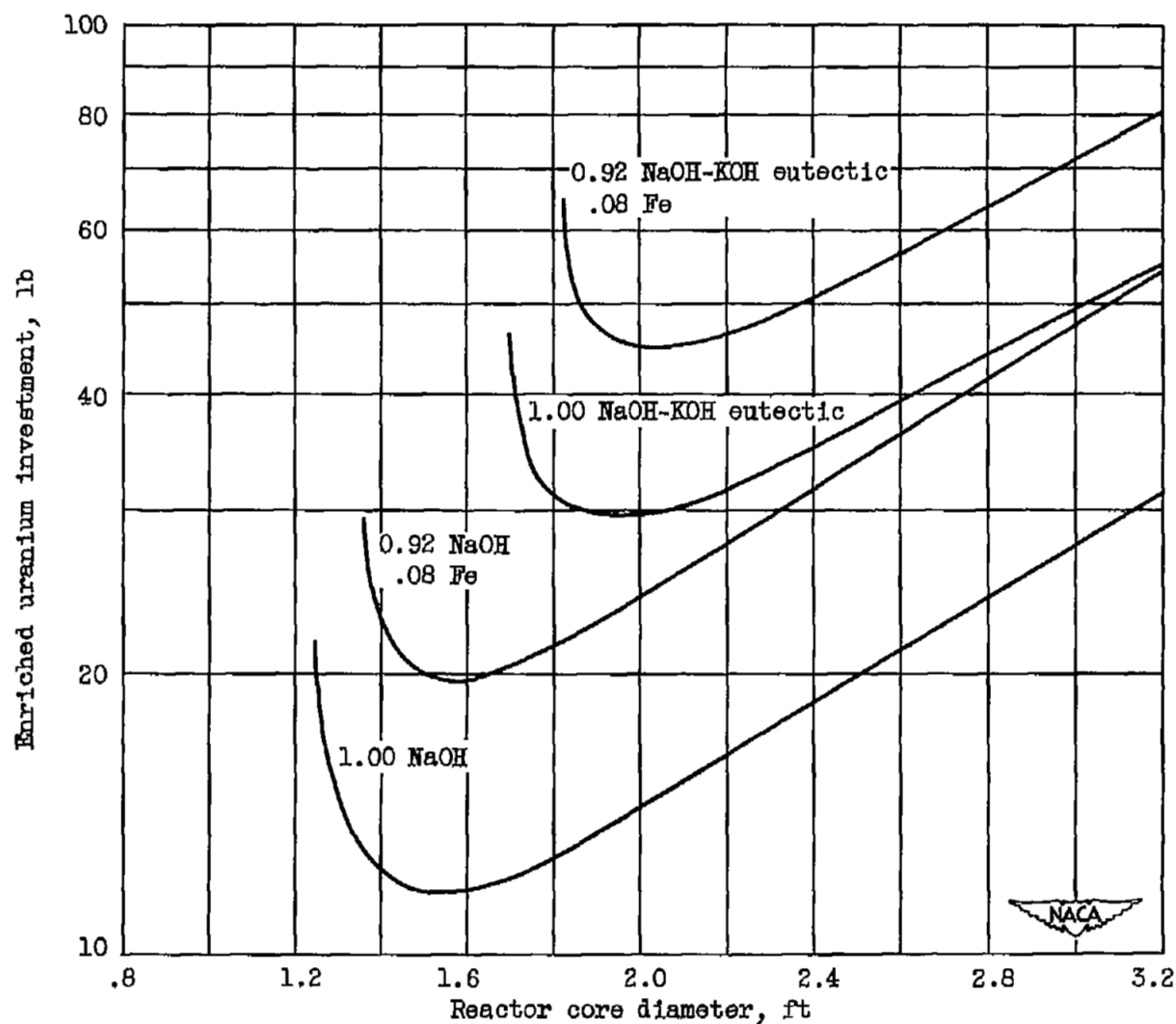


Figure 2. - Effect of iron on uranium investment for hydroxide cooled, moderated, and reflected reactors; reflector thickness, 0.5 foot; length-diameter ratio of cylindrical core, 1.0; average moderator temperature, 1450° F.

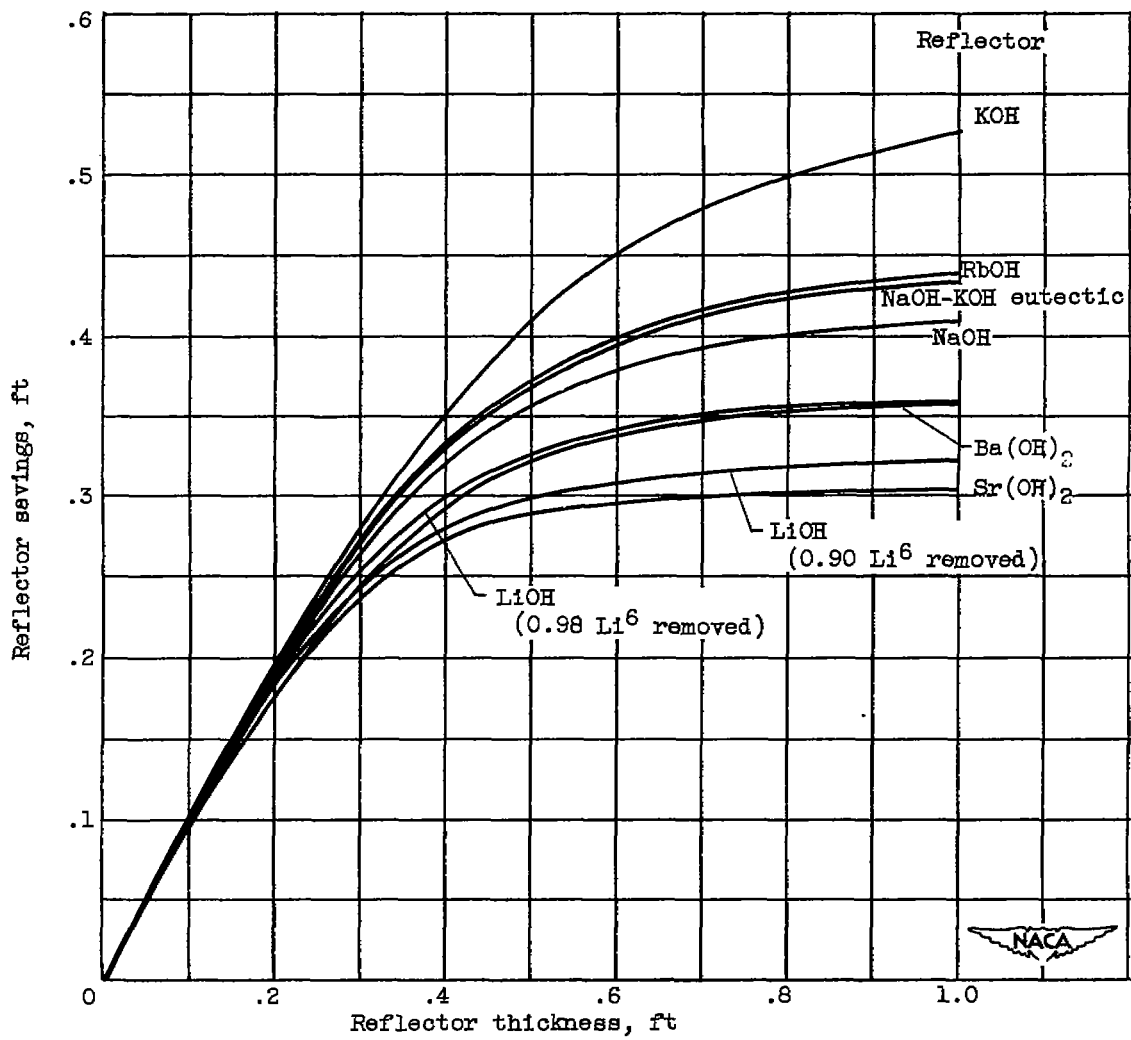


Figure 3. - Two-group reflector savings for hydroxide cooled, moderated, and reflected reactors.

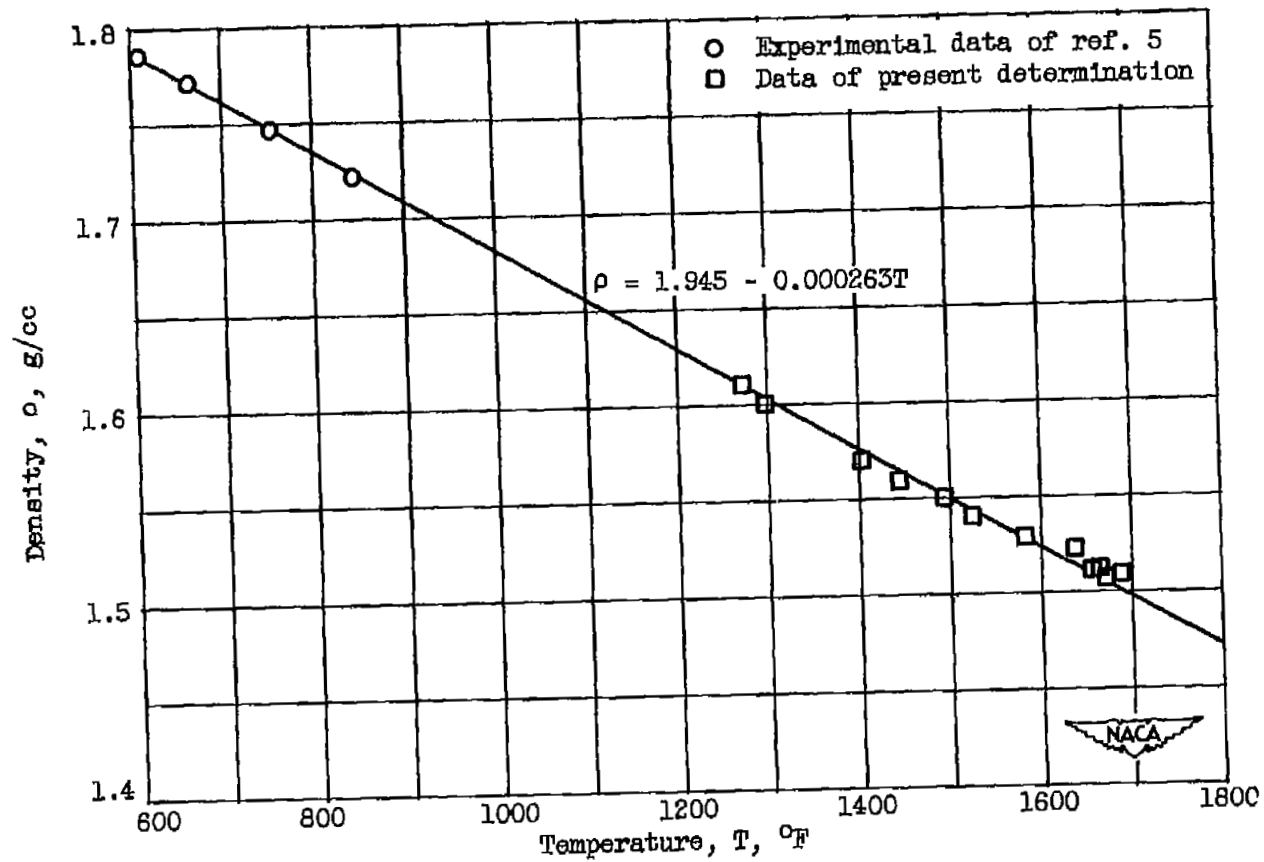


Figure 4. - Density of liquid sodium hydroxide.

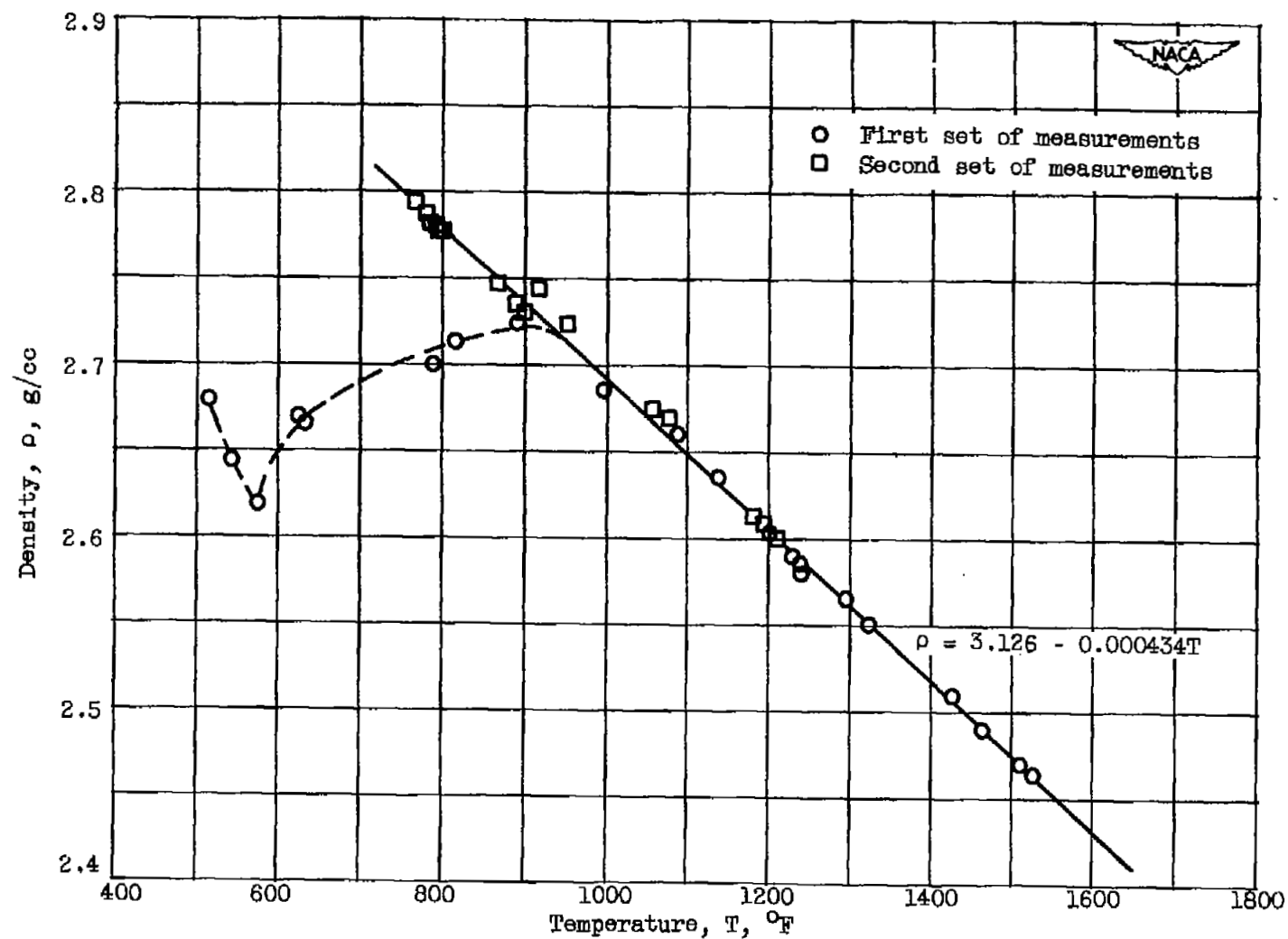


Figure 5. - Density of liquid rubidium hydroxide.

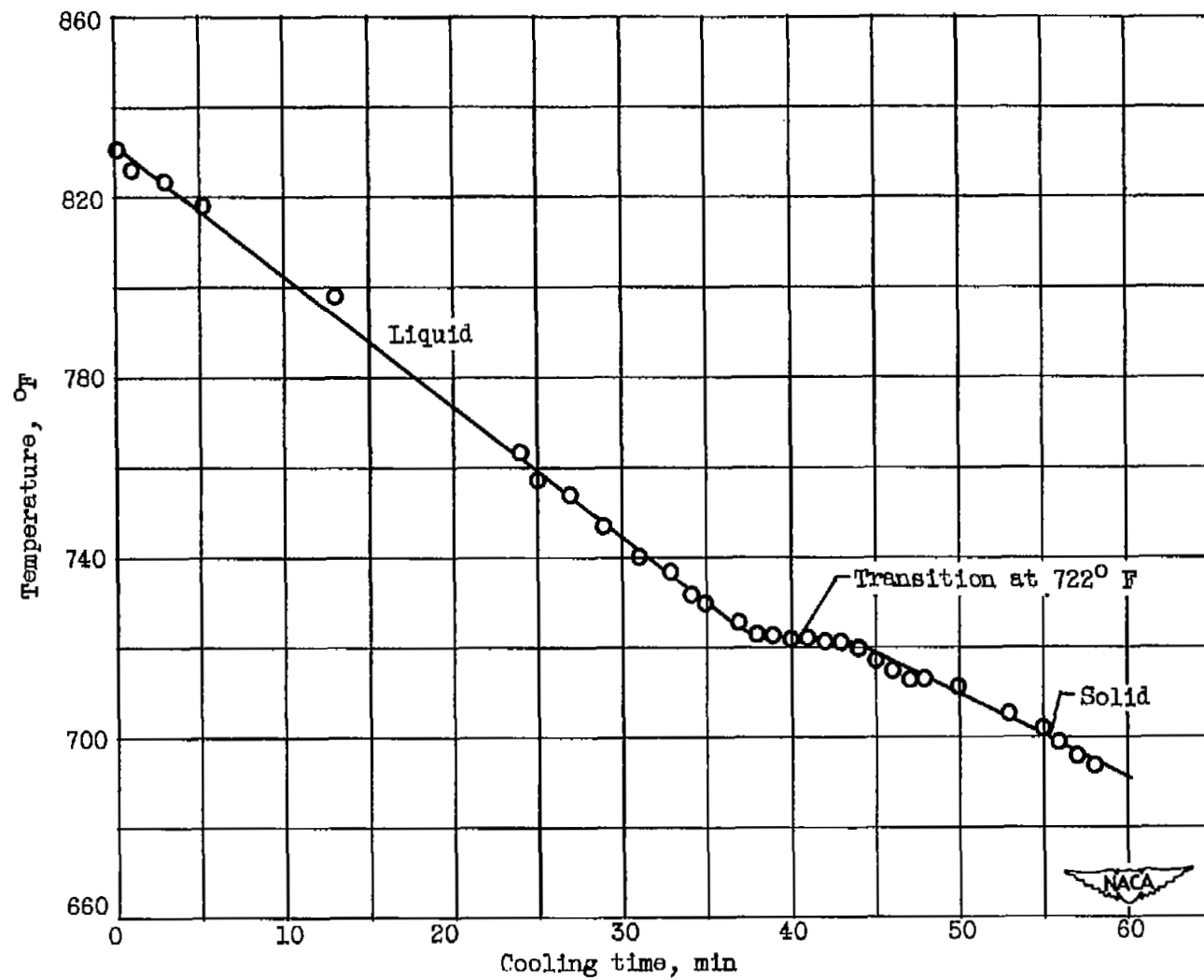


Figure 6. - Cooling curve for rubidium hydroxide.

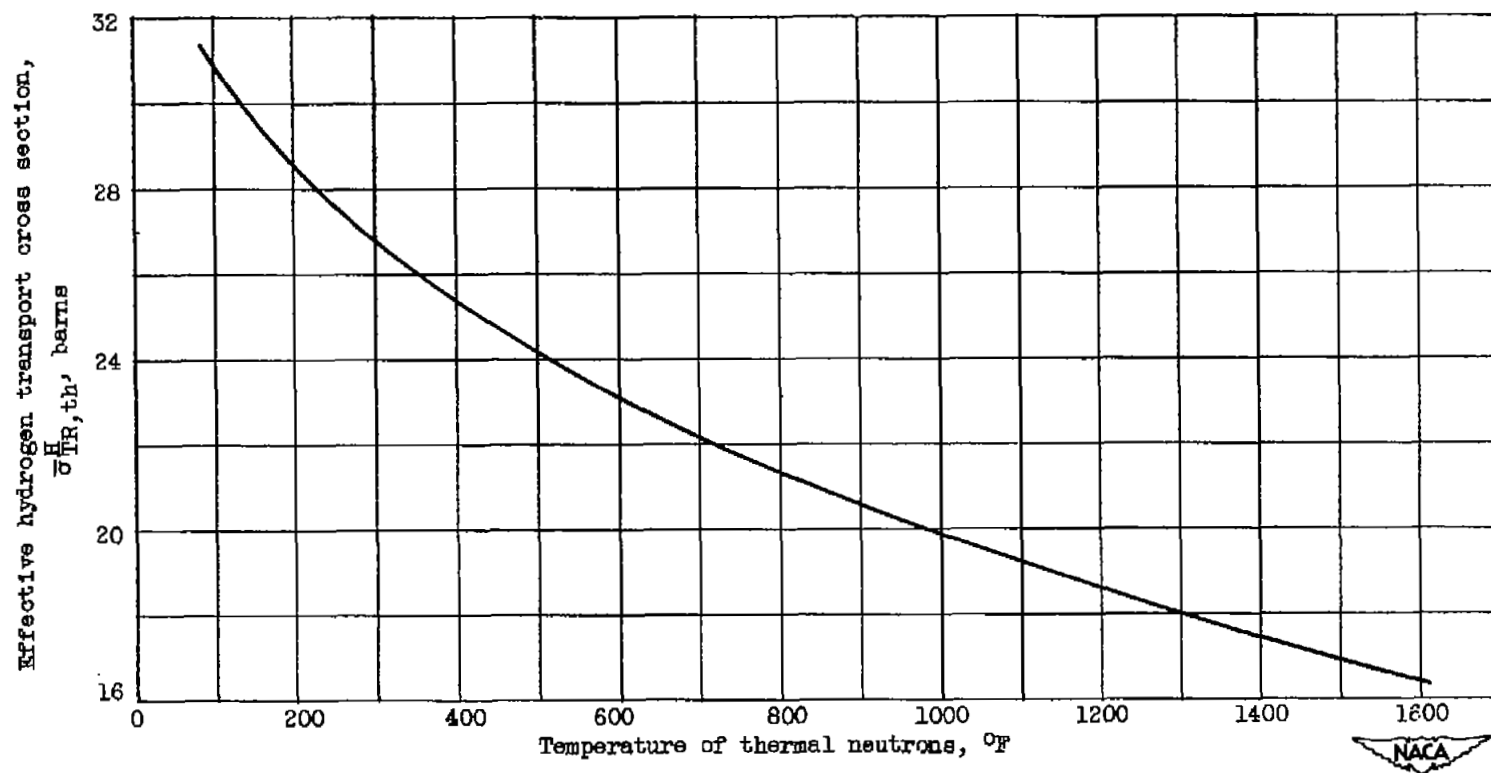


Figure 7. - Effective value of hydrogen transport cross section due to chemical binding for various thermal neutron temperatures.

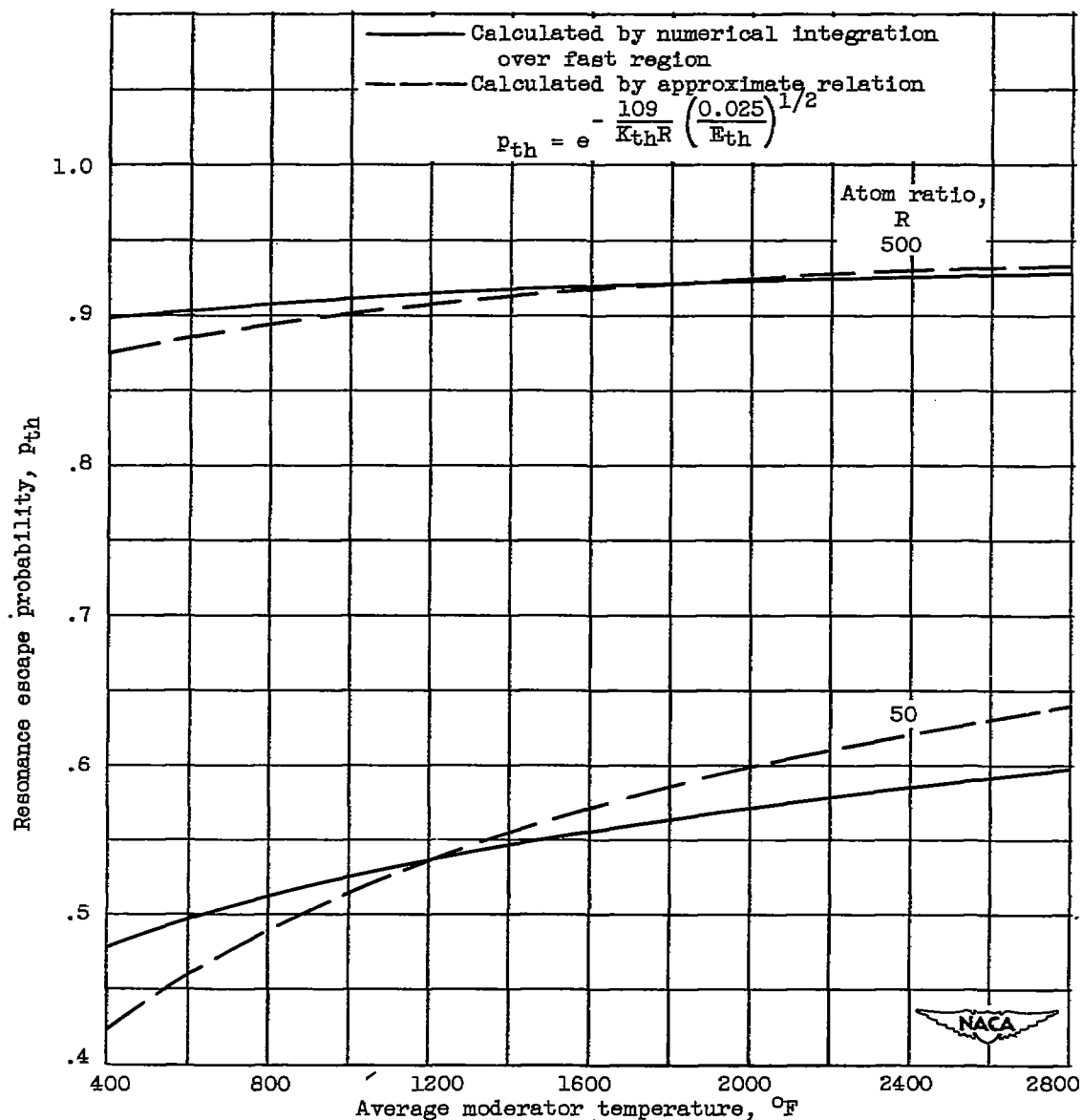


Figure 8. - Variation of resonance escape probability for NaOH-U infinite media with average moderator temperature.

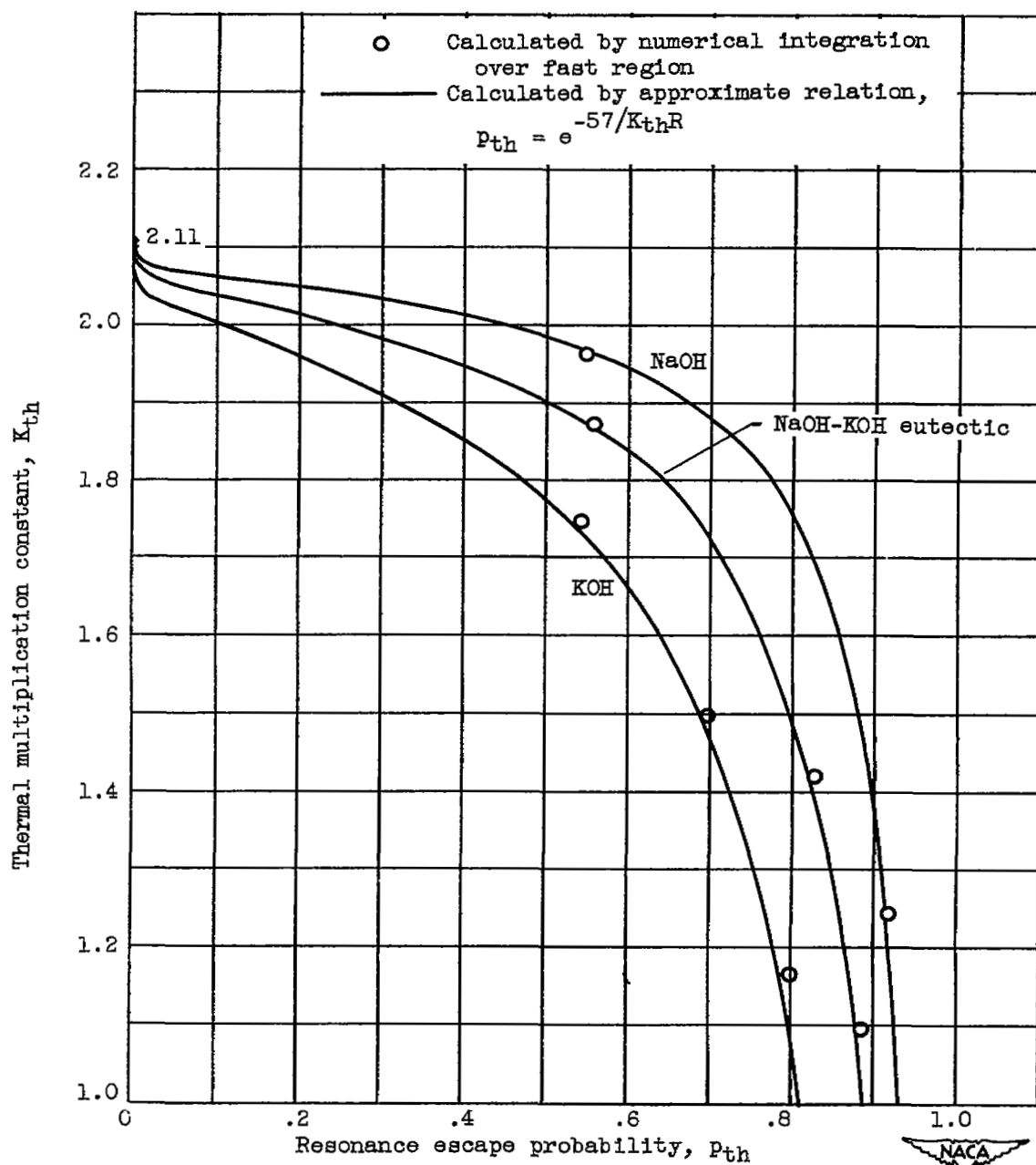


Figure 9. - Resonance escape probability for hydroxide-uranium infinite media for average moderator temperature of 1450° F.

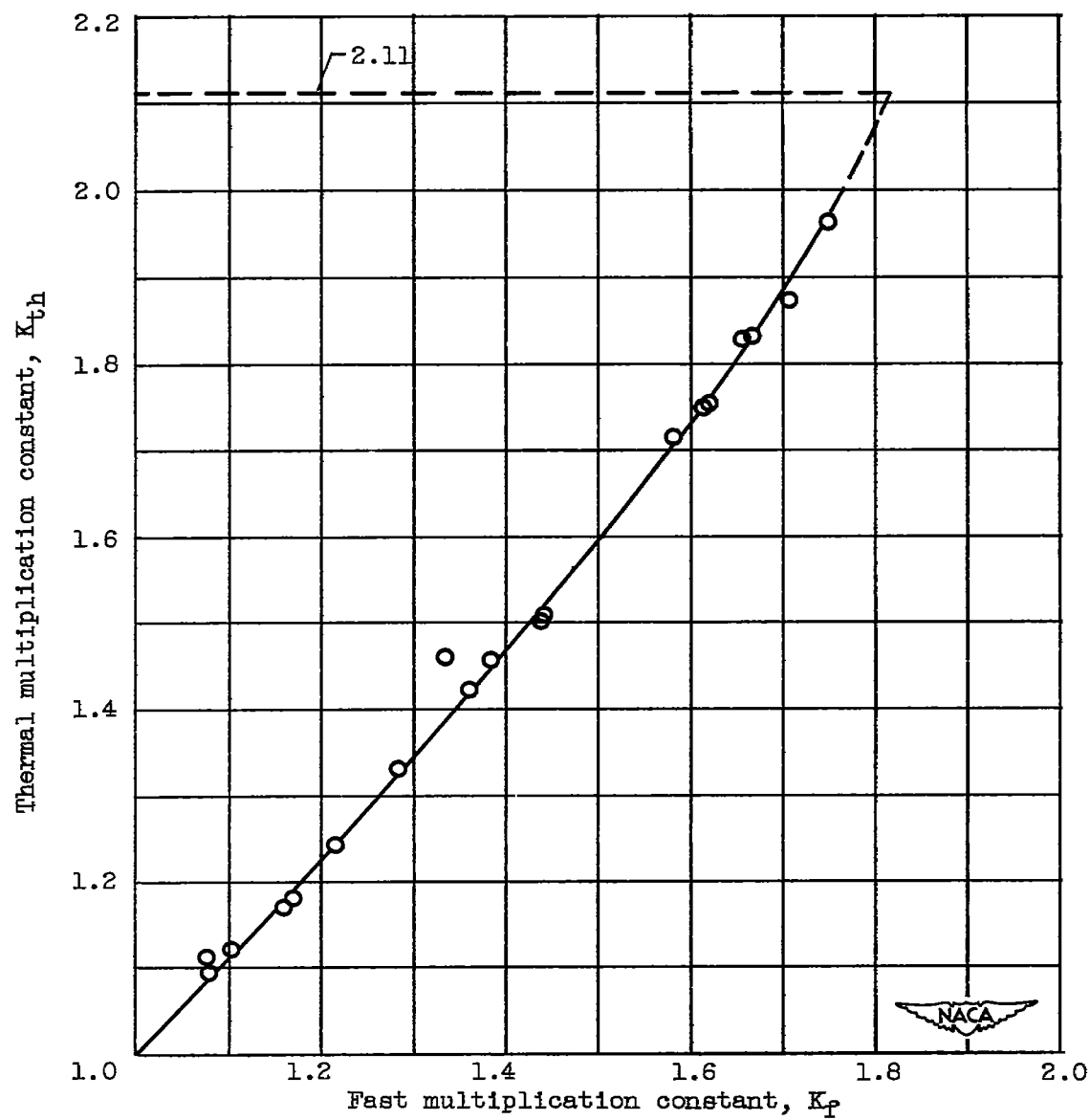


Figure 10. - Relation between thermal and fast multiplication constants.

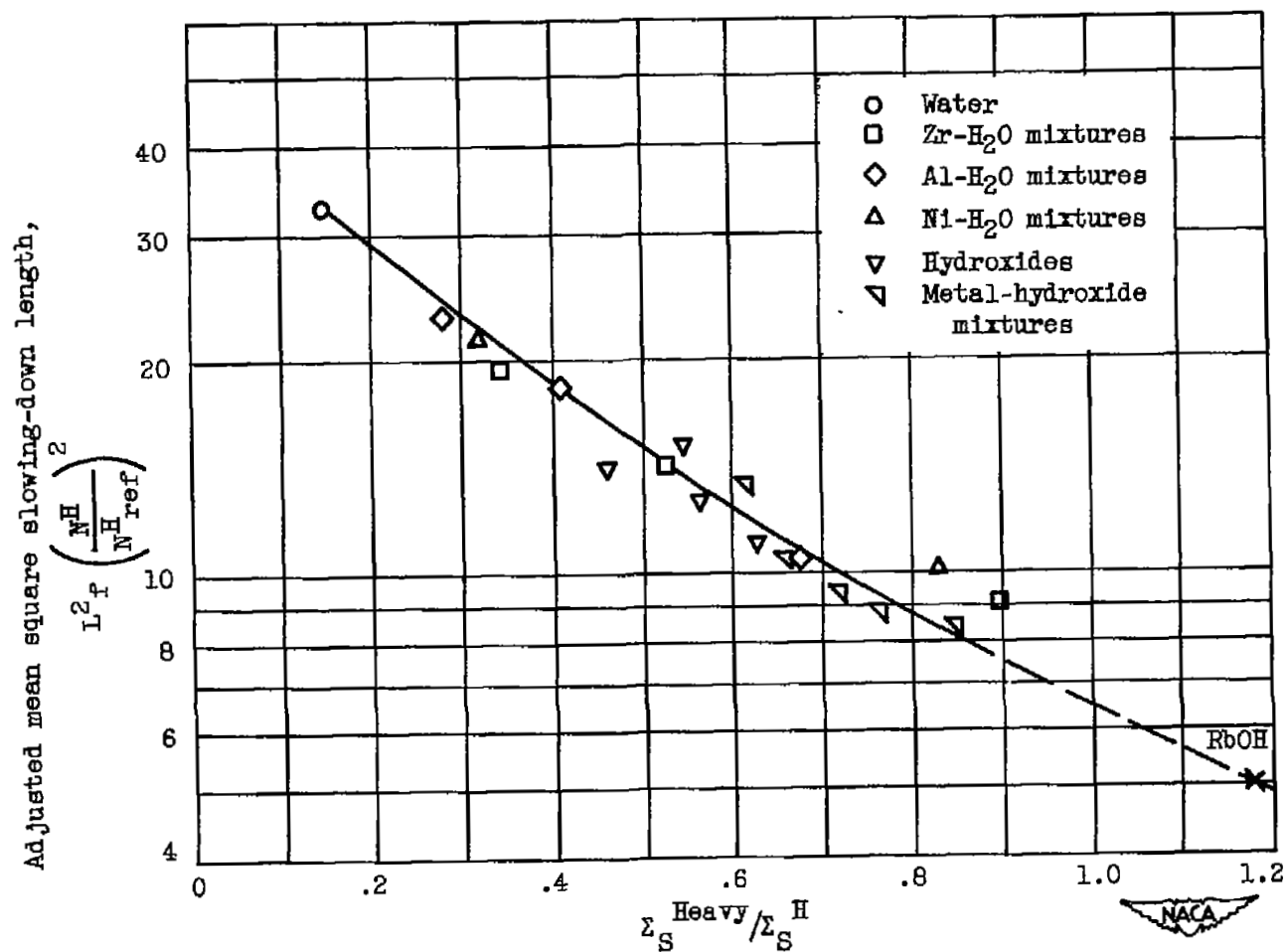


Figure 11. - Variation of adjusted mean square slowing-down length referred to water of unit density with relative scattering ratio. Values of L^2_f are calculated by procedures in reference 12.

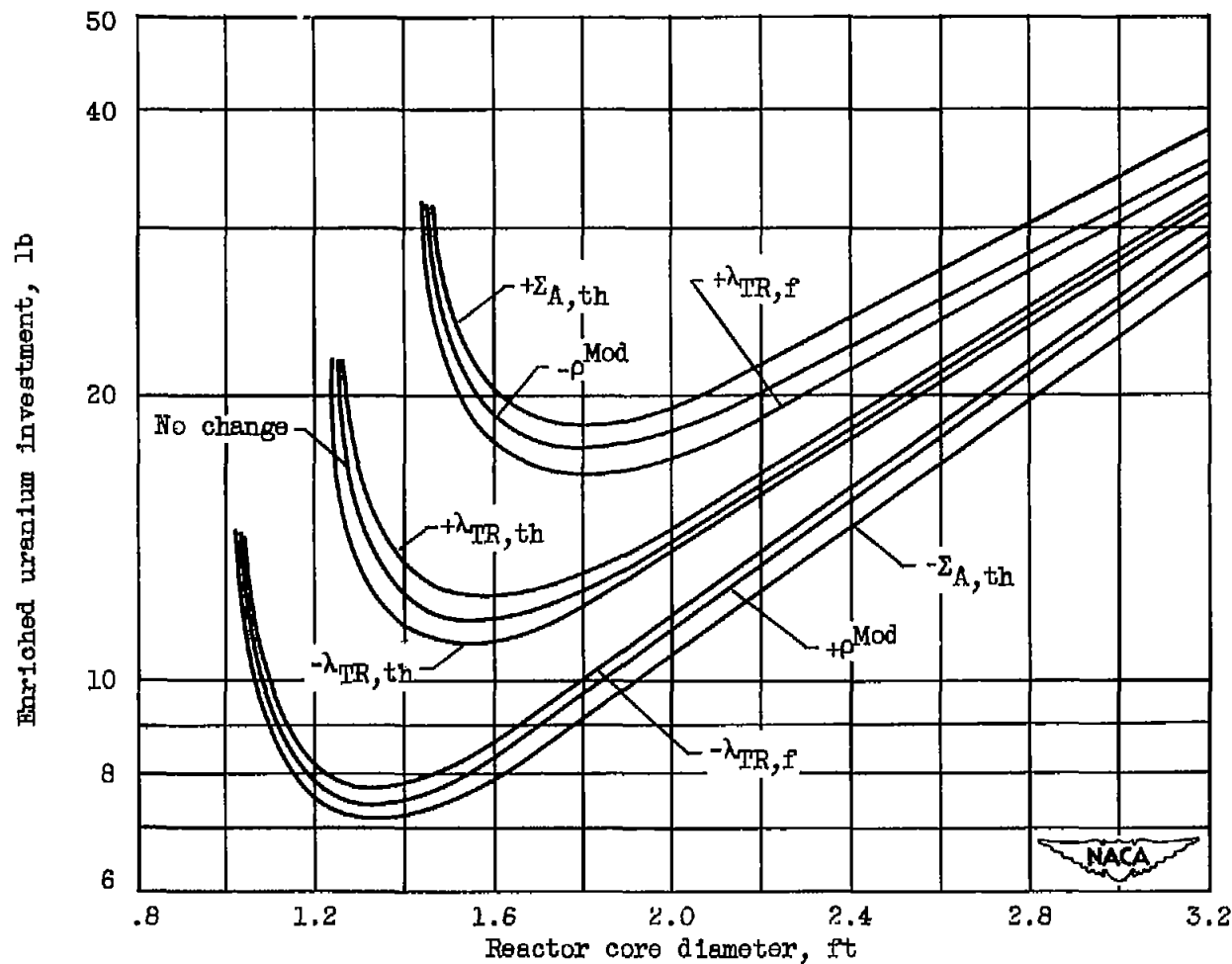


Figure 12. - Effects of arbitrary 10-percent variation in two-group constants on criticality predictions for sodium hydroxide cooled, moderated, and reflected reactors; reflector thickness, 0.5 foot; length-diameter ratio of cylindrical core, 1.0; average moderator temperature, 1450° F.

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